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EXPERIMENTAL CALIBRATION OF SEMICONDUCTOR DETECTOR PULSE-HEIGHT RESPONSE TO PROTONS

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FOREWORD

This report was prepared by the following personnel of the USAF School of Aerospace Medicine and the Texas Nuclear Corporation, Austin, Tex.

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A source of 16.5 ± 0.3 Mev protons was furnished by the Texas Nuclear Corporation, Austin, Tex. Dr. John H. William and Robert Featherstone made available 39.9± 0.3 Mev protons from the LINAC at the University of Minnesota. Through Dr. Borje Larrson, 185 ± 2 Mev protons were obtained from the 230 cm. synchrocyclotron at the University of Uppsala, Sweden.

ABSTRACT

Significant progress has been made toward accomplishing measurement of the energy absorbed from a proton as a function of the path length of the proton in the sensitive volume of a semiconductor detector. Surface barrier P-N and P-i-N detectors have been used in the study utilizing path lengths as short as 100 μ and as long as 10 cm. Protons of initial energy of 16, 40, and 187 Mev have been used. Other proton energies (8 to 166 Mev) were obtained by using absorbers in the proton beam. Energy calibrations were accomplished by total absorption of protons of known energy.

This technical documentary report has been reviewed and is approved.

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EXPERIMENTAL CALIBRATION OF SEMICONDUCTOR DETECTOR PULSE-HEIGHT RESPONSE TO PROTONS

1. INTRODUCTION

A study of the response of surface barrier P-N and P-i-N semiconductor detectors to protons was accomplished during the past three years. The purpose of the overall study was to determine applications of the semiconductor detectors to radiobiologic problems (1). The response of each detector was carefully measured in terms of the energy absorbed in its sensitive volume for alpha particles, electrons, photons, and protons. More than 100 different detectors representing the products of many different manufacturers were utilized.

Primary beams were furnished by three different facilities. At each facility, the lower energy protons were obtained by using absorbers in the proton beam.

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2. MEASUREMENT OF PROTON ENERGIES

At each of the facilities, both the energy and the energy spread in the primary beam had been carefully measured. This known primary energy was used to calibrate experimentally the detector-electronic system as follows: The response of a low-noise level, deep-depletion depth P-N detector to Co^{60} gamma rays (fig. 1) permitted calibration of the system (detector, preamplifier, amplifier, and 400 channel analyzer) at one point of known energy, 1.1 Mev. A pulse generator introduced, between the detector and preamplifier, a voltage comparable to the voltage output of the detector.

The pulse generator was then used to verify the linear response of the electronic system over the anticipated range of energy measurements. Next, alpha particles from polonium

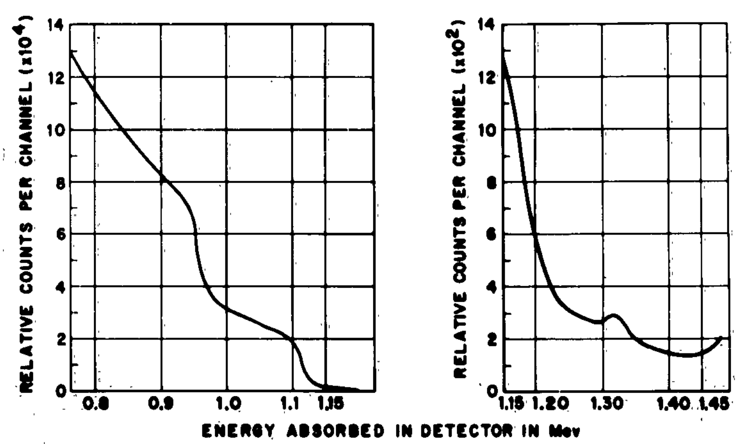

FIGURE 1

Gamma ray spectra of cobalt-60 obtained with a P-i-N detector.

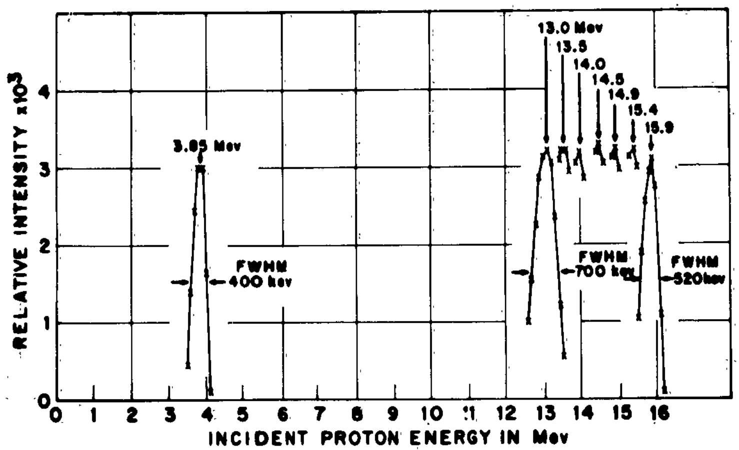

FIGURE 2

Response of P-N detector P-4 to totally absorbed 3.85 ± 0.2 Mev alpha particles and nearly monoenergetic protons. Multichannel analyzer channel width: 100 kev per channel.

having a measured average energy of 3.85 Mev were used to obtain experimentally both a channel number and a pulse-generator voltage corresponding to a 3.85 Mev pulse. Both the change in pulse-generator voltage per Mev and the change in channel number per Mev of absorbed energy permitted determination of the channels in which a pulse from a totally absorbed proton of known energy would be registered.

The detector was next oriented in the proton beam to provide a path length in silicon longer than the calculated range. The range in silicon for a 16 Mev proton is about 1.5 mm., for a 40 Mev proton it is about 7.6 mm., and for a 165 Mev proton it is about 8.6 cm. The spectral response of the energy absorbed in the detector from a beam of totally absorbed protons of 16 Mev energy is shown in figure 2 with the spectral line of 3.85 Mev alpha particles. The change in pulse-generator voltage per Mev and the change in channel position per Mev of energy absorbed were then compared to the values obtained over the 1.1 to 3.85 Mev energy range. Within the limits of experimental error, the change in channel position per Mev and the change in pulse-generator voltage per Mev were found to be constant between 1.1 and 16 Mev. After linearity response had been established, the shallow P-N detectors were calibrated using the alpha particles and the 16 Mev protons.

Dead layers on the surface and sides of the P-i-N detectors available at the time made it impossible to use 3.85 alpha particles for calibration of the system. Therefore, the cobalt-60 gamma rays and the 16 Mev protons were used to obtain calibration points for these detectors. A new type of P-i-N detectors is now available having lithium diffused into the silicon during the phosphorus treatment. These do not have a dead layer on the front surface. Polonium-alpha sources are suitable for calibration with this type.

Before each trip was made to a high-energy proton facility, the entire system (detector, preamplifier, amplifier, and 400 channel analyzer) was carefully calibrated for each detector over the range from 1.1 to 16.3 Mev as described above under operating conditions for which pulse-generator voltage calibration to a voltage equivalent to a 40 Mev or 185 Mev pulse gave a linear response over the desired range on the 400 channel analyzer. This calibration consisted of an accurate measurement of

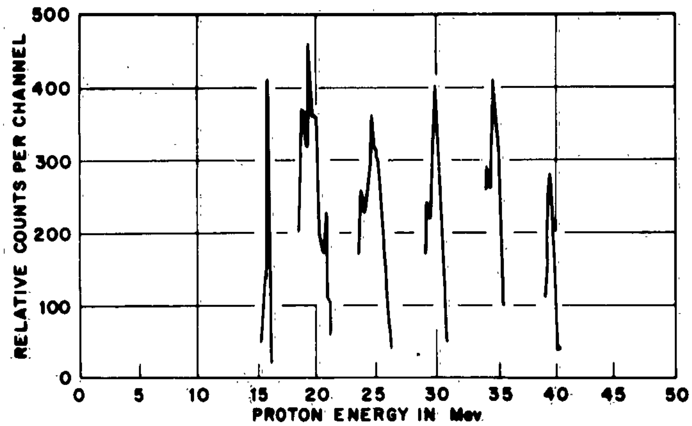

FIGURE 3

Response of a P-i-N detector to nearly monoenergetic protons totally absorbed in the detector.

change in channel number per Mev and change in pulse-generator voltage per Mev of energy absorbed. An on-site recalibration was accomplished by using radioactive isotopes and the pulse generator. After each trip, the calibration of the system was again checked over the range from 1.1 to 16.3 Mev energy absorbed.

Based on a calibration as described above, the charge pulses associated with the total absorption in silicon of protons of intermediate energies were measured. The intermediate energies were obtained by placing absorbing materials in the path of the primary protons. The energy absorbed was calculated by using Sternheimer's (2) range-energy tables. The protons emerging from the absorbing material had a wider energy spread than that of the primary beam. Range straggling, energy straggling, and low-angle scattering all contribute to this spread.

As shown in figure 3, the increasing energy spread in the beam is quite apparent in the spectral response of a P-i-N detector. The rest of the data presented in this paper represent only primary and intermediate energies having a beam spread of not more than ± 0.6 Mev for the 16 Mev protons, ± 0.6 Mev for the 40 Mev protons, and ± 4 Mev for the 185 Mev protons. Useful data obtained from the other modified beam energies will be discussed in another paper. The modified proton energies which were usable as reasonably narrow energy-band protons were 13.5 to 16.3 Mev, 30 to 40 Mev, and 104 to 185 Mev.

3. MEASUREMENT OF THE DEPTH OF THE SENSITIVE VOLUME

Since the charge collected from a detector is proportional to the loss of energy by an incident particle in the sensitive region, protons which are totally absorbed in this region will produce corresponding pulses of larger amplitude than protons of higher energy which pass completely through. Considering monoenergetic protons whose range is somewhat greater than the depth of the depletion region, the charge-pulse amplitude from the detector will increase with decreasing proton energy until the proton range and sensitive depth are equal. A further decrease in proton energy will cause a proportionate decrease in the charge pulse. Thus, if the protons are passing through the sensitive volume at normal incidence to the surface of the detector, the maximum charge pulse measured in energy-spectral analysis will correspond to the proton energy having a range just equal to the depth of the sensitive volume.

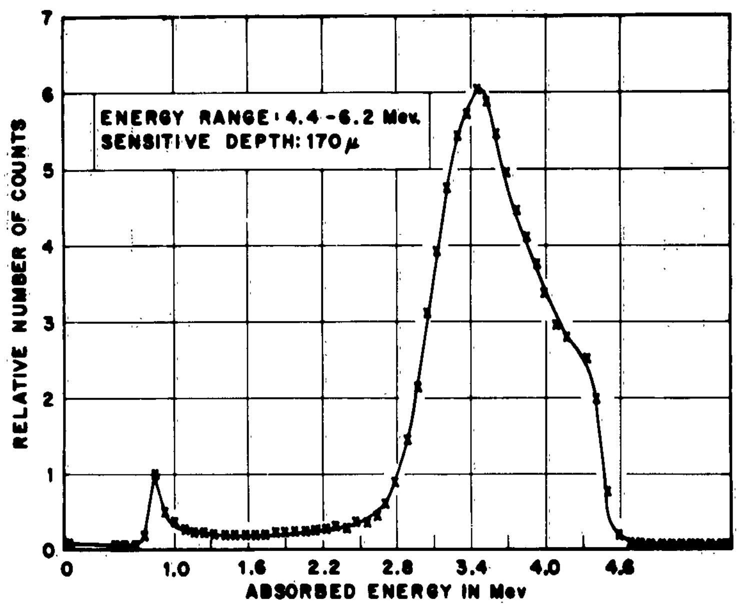

FIGURE 4

P-N detector P-2 response to protons having an average energy of 5.3 Mev.

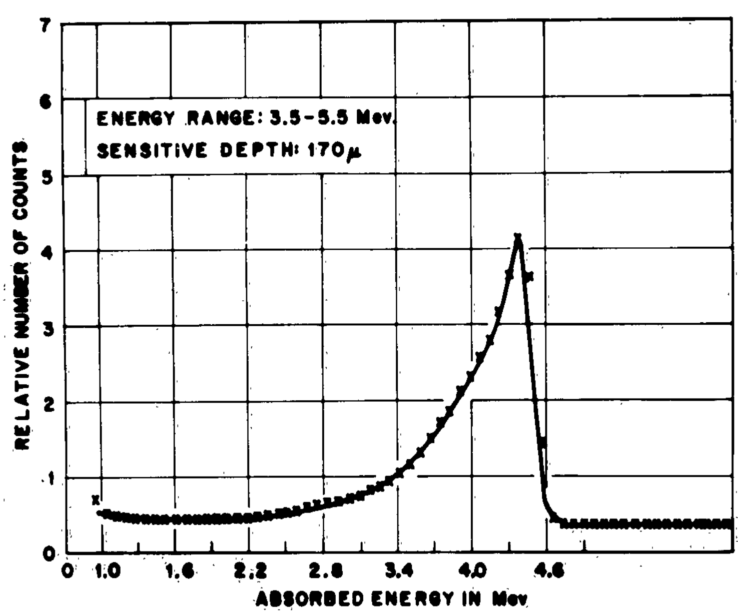

FIGURE 5

P-N detector P-2 response to protons having an average energy of 4.5 Mev.

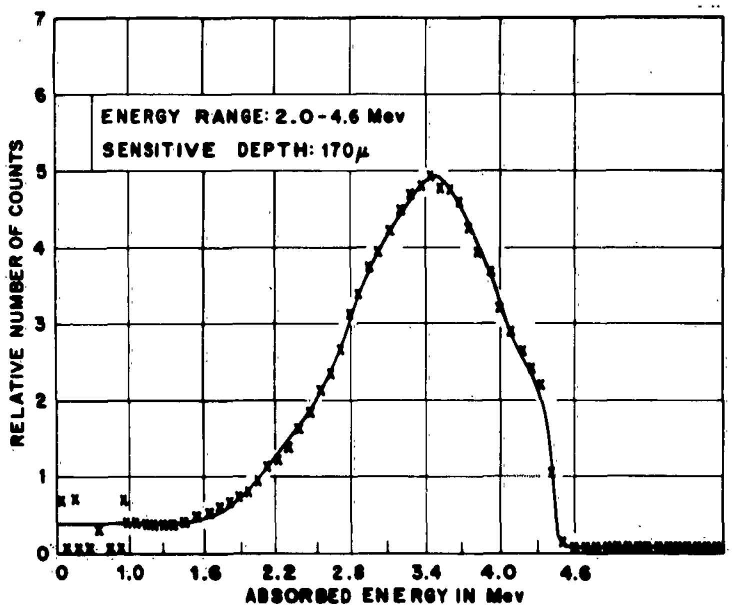

FIGURE 6

P-N detector P-2 response to protons having an average energy of 3.4 Mev.

Let us assume that a proton beam has such a broad spread of energies that all but the very lowest are sufficient to carry the proton completely through the sensitive volume of the detector. For such a beam, the response of a P-N detector would be as shown in figure 4. The higher the proton energy, the less is the charge pulse created in the detector. Reducing the overall energy of the beam to a point where the median energy is that at which total absorption occurs gives a response as shown in figure 5. The protons passing all the way through the sensitive volume give a pulse comparable to the pulse of lower energy protons totally absorbed. The "peak" apparently narrows and has one almost flat side due to this "fold-over" response.

If the overall beam energy is reduced further so that all the protons are totally absorbed (fig. 6), the shape of the spectral response curve is quite different from that of figure 5 or 4. It is possible to measure the depth of the sensitive volume from any of the three broad energy-band response curves. For the P-N detector used in this study, the maximum channel corresponded to a totally absorbed energy of 4.5 Mev. A proton having this energy has a range of 170 μ in silicon.

The standard procedure used involved measuring the depth of the sensitive volume at normal incidence. The detector was then rotated 60 degrees and this "double depth" was measured in the same way. Proton energy-absorption measurements made in this way for depths and "double depths" less than 1.5 mm. (range in silicon of 16 Mev protons) have shown agreement within 20 μ.

Measurement of the depth of a sensitive volume for P-i-N detectors having a dead layer on the surface requires a different technic. The overall energy of the beam is reduced to locate the fold-over phenomena just discussed. Because of the deeper sensitive depths of the P-i-N detectors, the proton energies are usually high enough to be considered monoenergetic, ± 0.3 Mev.

TABLE I

Energy absorbed from proton traveling through silicon.

Measured value* (Mev)	Incident proton energy† (Mev)	Measured value	Calculated value	Measured value	Calculated value	Measured value	Calculated value
		Silicon path = 170 μ		**Silicon path = 340 μ**		**Silicon path = 680 μ**	
13.5 ± .2	13.5	1.2 ± .2	1.26	2.5 ± .2	2.6	5.8 ± .2	5.7
14.0 ± .2	14.0	1.2 ± .2	1.22	2.5 ± .2	2.5	5.5 ± .2	5.5
14.5 ± .2	14.5	1.2 ± .2	1.18	2.4 ± .2	2.4	5.2 ± .2	5.2
14.9 ± .1	14.9	1.1 ± .1	1.15	2.3 ± .1	2.4	5.0 ± .1	5.1
15.4 ± .1	15.4	1.1 ± .1	1.12	2.3 ± .1	2.3	4.8 ± .1	4.9
15.9 ± .1	15.9	1.1 ± .1	1.10	2.2 ± .1	2.2	4.6 ± .1	4.7
16.3 ± .1	16.3 ± .3	1.1 ± .1	1.07	2.2 ± .1	2.1	4.5 ± .1	4.6
30.0 ± .4	30.0			1.4 ± .2	1.3	2.8 ± .2	2.6
35.0 ± .3	35.0			1.3 ± .2	1.2	2.5 ± .2	2.4
39.7 ± .3	39.7 ± .3			1.0 ± .1	1.1	2.0 ± .1	2.1
		Silicon path = 5 mm.		**Silicon path = 1 cm.**		**Silicon path = 3 cm.**	
	30.0	30.0 ± .2	30.0	30.0 ± .2	30.0		
	35.0			35.0 ± .1	35.0		
	39.7			39.7 ± .1	39.7		
104.0 ± 4.0	104.0	7.2 ± .6	7.2	15.0 ± .6	15.1	52.0 ± 4.0	54.0
118.0 ± 4.0	118.0	6.5 ± .6	6.6	12.8 ± .6	13.7		46.0
132.0 ± 4.0	132.0	6.1 ± .4	6.1	12.1 ± .4	12.4		41.0
144.0 ± 2.0	144.0	5.8 ± .4	5.8	11.8 ± .4	11.8		37.9
155.0 ± 2.0	155.0		5.5	11.2 ± .4	11.0	36.0 ± 2.0	35.4
165.0 ± 2.0	165.0 ± 2.	5.2 ± .2	5.1	10.9 ± .4	10.6		33.4
	185.0	4.9 ± .2	4.8	9.9 ± .2	9.9	31.0 ± 1.0	30.5
		Silicon path = 10 cm.					
	185.0	130.0 ± 4.0	133.0				

*The experimental error as given for the measured values indicates the precision of the location of the peak of the detector response curve.

†The spread in the energy of the incident proton beam for the 16.3, 39.7, and 165 Mev values indicates the accuracy to which the primary proton beam energies were known. The other values for incident energy were calculated from Sternheimer's range-energy tables.

The energy of the incident proton energy is thus known to within about 3%. The maximum energy absorbed is measured directly with a calibrated system. The difference represents the energy absorbed in the dead layer. The detector is rotated 60 degrees, keeping the incident proton energy constant. The maximum energy absorbed is again measured. The difference now is equal to the energy absorbed in the "double thick" dead layer. Therefore,

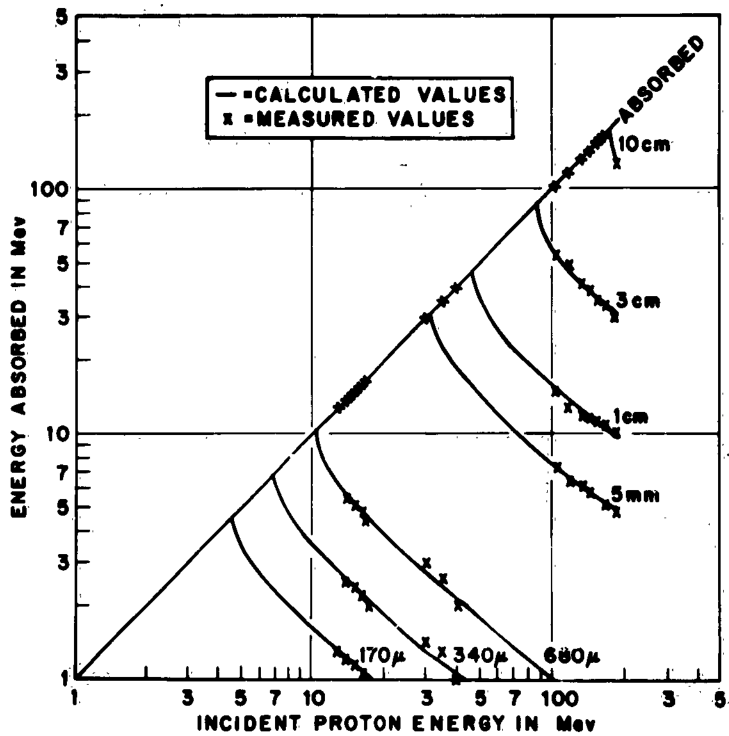

FIGURE 7

Energy absorbed in silicon from protons.

two measurements are possible on the thickness of the dead layer and one on the depth of the sensitive volume.

4. DATA

Typical data obtained are given in table I and plotted on figure 7. The data for 170 μ represent a P-N detector oriented for normal incidence (through the front surface) of the protons. The sensitive path length was doubled by rotating the detector 60 degrees. A number of P-i-N detectors were prepared by Hughes Research Laboratories for this research effort. One of the P-i-N detectors had a 340 μ width of sensitive volume at 0 degree, and 680 μ at 60 degrees. The detectors are 5 by 5 mm. in cross section, and range in length from 1 to 10 cm. The data for 5 mm. represent the average value for protons entering the side of such detectors. Six different P-i-N detectors having path lengths of 1 cm. (protons entering through the end of the detector) were used. Three detectors having path lengths of 3 cm. (end entry) and one detector 10 cm. long were used in the study.

The data involving proton energies up to 40 Mev have been duplicated on more than one field trip and on enough different detectors for this phase of the research to be considered complete. The data obtained for the response of the 104 to 185 Mev protons represent one field trip and must be considered as preliminary.

5. CONCLUSIONS

1. Over an energy range of 1.1 to 40 Mev, the charge pulse created in a silicon semiconductor detector is directly proportional to the energy absorbed in the sensitive volume

whether the ionizing particle is totally absorbed or not. Preliminary data indicate that this is also true up to energies of 165 Mev.

2. The Sternheimer (2) range-energy tables for aluminum, when corrected for differences in density and charge between aluminum and silicon, give calculated values of energy absorbed in known path lengths of silicon. These values agree within experimental error to the measured values.

3. The calculated energy losses, using the Sternheimer (2) range-energy tables, give energy losses for protons passing through aluminum at energies up to 185 Mev and for lead up to 40 Mev that agree with the values measured.

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USAF School of Aerospace Medicine, Brooks AF Base, Tex.

SAM-TDR-63-21. EXPERIMENTAL CALIBRATION OF SEMICONDUCTOR DETECTOR PULSE-HEIGHT RESPONSE TO PROTONS. Mar. 63, 7 pp. incl. illus., tables, 2 refs.

Unclassified Report

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2. Detectors, semiconductor

I. Task 775701
II. Crawford, G. W., Alexander, T. A., Spetzler, H. A. W., et al.
III. In ASTIA collection

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